Measurements of Beam Current Density and Proton Fraction of a Permanent-Magnet Microwave Ion Source *

O. Waldmann[a] and B. Ludewigt[a]
[a]Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720

11/16/2011

Abstract

A permanent-magnet microwave ion source has been built for use in a high-yield, compact neutron generator. The source has been designed to produce up to 100 mA of deuterium and tritium ions. The electron-cyclotron resonance condition is met at a microwave frequency of 2.45 GHz and a magnetic field strength of 87.5 mT. The source operates at a low hydrogen gas pressure of about 0.15 Pa. Hydrogen beams with a current density of 40 mA/cm^2 have been extracted at a microwave power of 450 W. The dependence of the extracted proton beam fraction on wall materials and operating parameters was measured and found to vary from 45% for steel to 95% for boron nitride as a wall liner material.
Keywords: Ion sources; Plasma heating by microwaves; ECR, LH, collisional heating; Plasma sources; High-frequency and RF discharges

1 Introduction

Compact, high-yield neutron generators are needed for homeland security, nonproliferation, and industrial applications. In such generators, typically designed as a sealed tube, deuterium (D) and tritium (T) ions are extracted from an ion source and accelerated onto a deuterated metal target (Ti or Mo) where neutrons are produced in D-T and/or D-D fusion reactions. Penning ion sources have successfully been used in the past. However, they are limited in extracted beam current density and produce only a small atomic ion fraction which leads to lower neutron production efficiency. Radio-frequency-driven (RF) ion sources have been developed for neutron generators that produce high beam current densities and high atomic fractions but are difficult to operate at the low gas pressures in a sealed tube generator [1, 2].

Microwave-driven ion sources, in contrast, operate at low gas pressures ($\approx$ 0.15 Pa), produce high current densities, high atomic fractions, and are more power efficient than RF ion sources. The permanent-magnet microwave ion source presented here has been developed for a high-yield, sealed-tube neutron generator. In its final implementation a beam current of 100 mA will be extracted through a large 60×6 mm^2 slit by an acceleration voltage of 100 kV to produce a neutron yield that exceeds $5 \cdot 10^{11}$ n/s in D-T operation. The required beam density is $j_{DT} = 25$ mA/cm^2.

The ion source tests reported here were conducted with a small extraction aperture and with hydrogen gas to avoid the generation of neutrons. A hydrogen extracted beam density of $j_H = 40$ mA/cm^2 corresponds to the D-T beam density of $j_{DT} = 25$ mA/cm^2 under otherwise identical conditions.

This article describes the ion source design and presents experimental data for the dependence of extracted beam current density and ion species fractions on microwave power, gas pressure, and ion source wall materials.

2 Ion Source Design

The ion source consists of an aluminum cylinder (100 mm long and 90 mm in diameter) with a ferromagnetic steel front plate and a stainless steel back plate, cf. Fig. 1. The ferromagnetic front plate confines the magnetic field lines and lowers the magnetic field in the extraction area outside the source drastically. The simulation studies and measurements of the magnetic field were published earlier [3]. The use of the ferromagnetic front plate made it possible to attach the ion source to the existing neutron generator tube [1]. The dimensions of the source are based on earlier developments which used either magnetic field coils [4, 5] or permanent-magnet rings without a ferromagnetic front plate [6]. For the tests discussed here a small extraction aperture of 3 mm in diameter was chosen to limit the extracted beam current.

The back plate is water-cooled and has an opening for a vacuum window. The vacuum window itself is made out of quartz. Quartz was chosen as the window material because it can be implemented in a brazed, ultra-high vacuum compatible version for a sealed generator tube. It is protected on the plasma side by an additional dielectric sheet of aluminum nitride. In the experiments described here a viton o-ring seal was used. The gas is inserted through the back plate. An additional gas line allows to measure the gas pressure inside the source with a Baratron-type ion gauge.

In order to achieve efficient coupling of the microwave power with a frequency of 2.45 GHz into the plasma, a magnetic field of $B = 87.5$ mT is applied to meet the electron-cyclotron resonance (ECR) condition ($\omega_{\mathrm{ECR}} = \frac{e}{m}B$, with e as the electron and m as the electron mass). Earlier experiments on magnetic field strength at the vacuum window showed that meeting the ECR condition

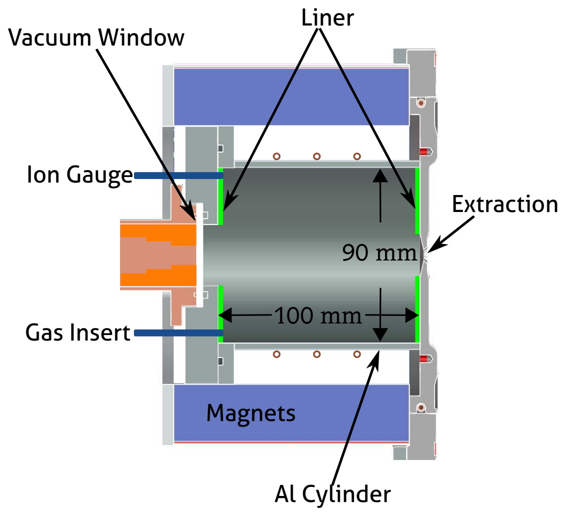

Figure 1: Schematic of ion source. Front plate made of ferromagnetic steel.

right at the window-plasma transition is crucial for good power coupling [3]. The magnetic field is generated by permanent NdFeB-magnets. Seven stacks of rectangular, "off the shelf" magnets are arranged around the source cylinder and extend beyond the back plate, cf. Fig. 2. The magnets are placed behind water cooling lines to avoid demagnetization due to high temperature [7].

NdFeB-magnets are known to be impacted by neutron irradiation. Alderman et al. [8] showed the decrease in residual induction is below 1% for fluences up to $2.3 \cdot 10^{13}$ neutrons/cm^2. Assuming a point source of neutrons at the target, a simple estimate shows that this limit is reached for magnets at a distance of 200 mm after roughly 3200 h and 100 h in D-D and D-T operation, respectively. Therefore, for long lifetime operation in D-T mode the NdFeB-magnets would have to be replaced by SmCo-magnets, which have no reported magnetic flux loss up to $5 \cdot 10^{19}$ neutrons/cm^2 [9].

The microwave system used in the experiments consisted of a microwave generator, a three-stub tuner, a circulator, and a high-voltage break. A ridged waveguide was used to launch the microwave through the window into the plasma and to optimize the coupling of the microwave power to the plasma.

3 Measurements

3.1 Beam Current Density

The extracted beam current density was measured with a Faraday cup and the change in current with microwave power and source pressure was investigated.

Fig. 3 shows the increase in beam current density with increasing microwave power from 400 W to 600 W at a hydrogen gas pressure of 0.14 Pa. The

Figure 2: Photo of ion source. The magnetic bars are visible

target beam density of $j_H = 40$ mA/cm^2 is reached at 450 W. This power is significantly lower than the ≈ 1.5 kW required for an earlier developed RF-driven ion source for producing the same beam current density [1].

In a sealed and not actively pumped neutron generator tube stable ion source operation is needed at a low pressure, typically in the range of $0.1 - 0.3$ Pa. We have measured the extracted beam current for gas pressures from $0.1 - 0.55$ Pa, cf. Fig. 4, at a microwave power of 400 W. The beam current density decreases linearly with increasing pressure and is 10% lower at 0.55 Pa than at 0.13 Pa. The discharge becomes unstable below 0.1 Pa. This behavior can be explained by the collisionality of a plasma. At very low pressures the chance for an ionizing collision between an electron and neutral species is too low and a plasma can not be sustained. If the pressure is too high, the electron collides with a neutral species before it gains enough energy to ionize and hence the degree of ionization of the plasma, i.e. the plasma density, is reduced.

3.2 Proton Fraction

In a neutron generator the yield is proportional to the energy integral of the cross-section [10]. Since for a given acceleration voltage a molecular hydrogen ion gains a half or a third of the kinetic energy per nucleon of an atomic ion, the highest proton fraction gives the highest neutron yield at a given acceleration

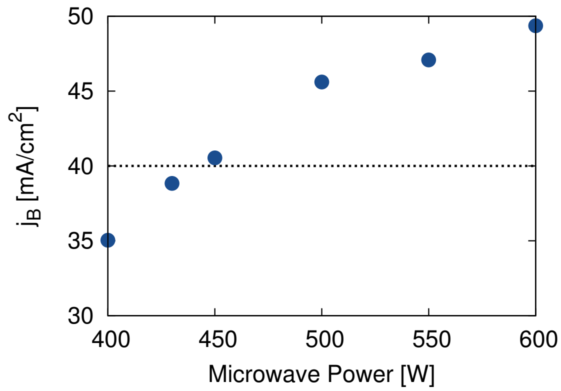

Figure 3: Increase of beam current density with microwave power at a pressure of 0.14 Pa.

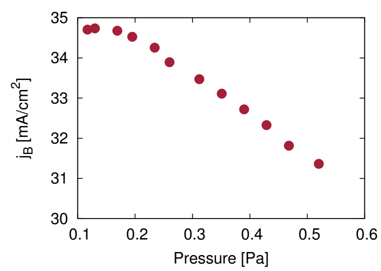

Figure 4: Decrease of beam current density with source pressure at a microwave power of 400 W.

voltage. The generator for which the ion source has been developed operates at a nominal acceleration voltage of 100 kV so that diatomic ions are accelerated to an energy of 50 keV per deuteron while the atomic ions reach 100 keV. This leads to a five times higher neutron yield [10] for the latter.

The plasma parameters in a source with a high ratio of wall area to volume are strongly determined by plasma-wall interaction. The wall material influences dissociation, ionization, and recombination of the plasma and, therefore, affects the atomic composition of a plasma [11]. Earlier works reported that certain dielectric materials increase the atomic fraction in a hydrogen plasma but did not compare them with each other or with non-dielectric materials [12].

Since the most important interactions take place between the charged particles and the wall, we placed liners where the magnetic field lines and therefore the charged particles hit the walls, i.e., at the front and end plates of the ion source. The aluminum wall of the cylinder was not covered.

The impact of four different wall materials on ion species distribution was investigated. Steel by virtue of being the material of the front and back plates, aluminum as an alternative conducting material, which has been reported to build an oxide layer on its surface [13], and alumina and boron nitride as dielectric materials that were reported to have a higher secondary electron yield [14, 15, 16] and a lower recombination probability [17] than metals. Increasing the number of secondary electrons and lowering the recombination rate leads to a higher degree of ionization.

The ion beam composition was analyzed in a magnetic spectrometer after pumping down the source with a $1,000$ l/s turbo pump (base pressure approx. 10^{-6} Torr) and conditioning the source with each liner until the total fraction of impurities was about 1%. For boron nitride liners, which outgass considerably more than the other materials tested, this took typically $6 - 10$ hours of plasma conditioning. Once the source is conditioned the impurities, which consist mainly of water ions, i.e. HO^+, H_2O^+, and H_3O^+, stay low. The ion beam is extracted by biasing the source positively against a grounded extraction electrode, cf. Fig. 5. The spectrometer consists of a bending magnet, slit apertures, and a Faraday cup for measuring the current as function of magnetic field strength.

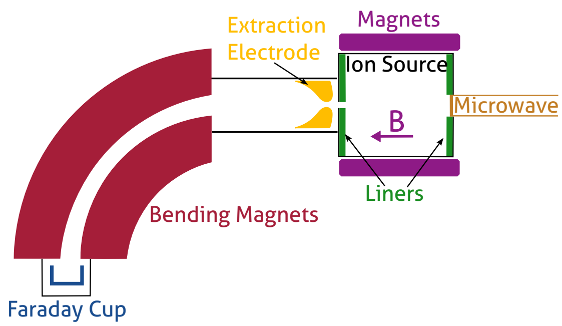

Figure 5: Setup for ion species measurement.

The results for different wall materials are compared in Fig. 6. The smallest proton fraction of just 45% was measured with steel end-caps. With aluminum liners the proton fraction increased to over 70%. The fraction is even higher for the two dielectrics. The proton fraction exceeded 80% with alumina liners and reached 95% with boron nitride liners.

Varying the pressure and the power has significantly less influence on the proton fraction than the choice of wall material. A higher source pressure leads to a higher recombination rate and therefore to a lower proton fraction, cf. Fig. 7. A higher input power leads to a higher electron temperature which leads to a higher ionization rate and a higher proton fraction, cf. Fig. 8. But in both cases we measured only small to moderate changes in the proton fraction. The highest increase can be found for alumina where the proton fraction increases with power from 72% at 350 W to 90% at 650 W. It is consistent with earlier studies that the beam density is nearly unaffected by boron nitride liners but the proton fraction increases dramatically in comparison with metallic walls [12, 18].

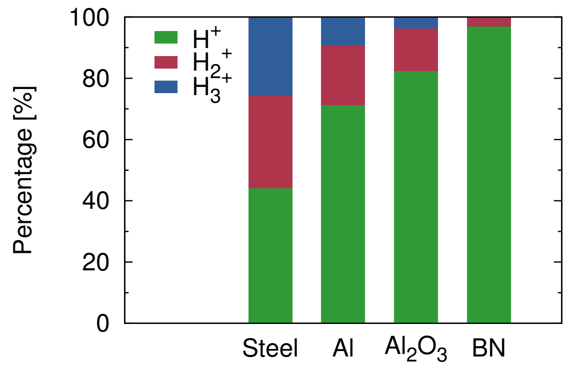

Figure 6: Proton fraction in an ion beam for different liner materials at 500 W and 0.13 Pa.

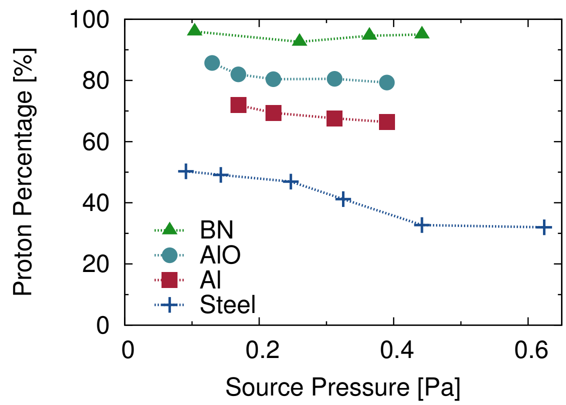

Figure 7: Change in proton fraction with source pressure at 500 W microwave power.

Boron nitride is the preferred liner material for front and end plates if the highest possible proton fraction is to be attained. Alumina and to a lesser degree aluminum are acceptable alternatives, whereas for steel the proton fraction drops below 50%.

4 Conclusions

A permanent-magnet microwave ion source with a high fraction of monoatomic hydrogen ions has been developed for use in a high-yield neutron generator. The source performs best at low pressures ($0.13 - 0.25$ Pa). The required beam current density of $j_H = 40$ mA/cm^2, equivalent to $j_{DT} = 25$ mA/cm^2, is reached at a microwave power of 450 W. Different wall liner materials covering the front and back plates of the cylindrical ion source were tested and the proton

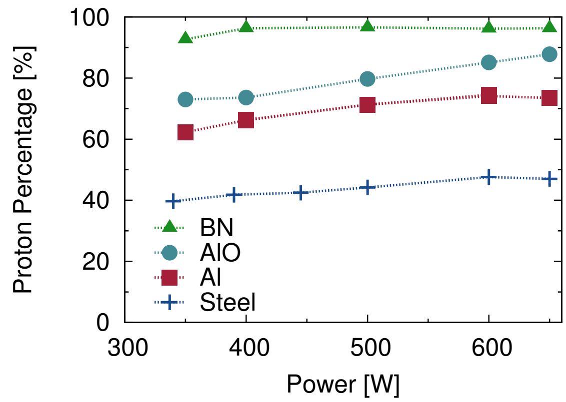

Figure 8: Change in proton fraction with microwave power at a pressure of 0.13 Pa.

fractions measured. Boron nitride increased the proton fraction to 95% but strong outgassing could make its use in a sealed tube neutron generator problematic. Alumina and aluminum liners, which increased the proton fraction to over 80% and over 70%, respectively, are good alternatives. For use of the ion source in the neutron generator, the small aperture will be replaced with a large, 60×6 mm^2 , slit for extracting a 100 mA D-T beam current onto a V-shaped neutron production target [1]. It is expected that the proton fraction will be similar to the results reported here for the same source operating parameters. A possible variation of the beam current density across the slit will impact the beam optics. However, this is acceptable as long as the ions reach the neutron production target.

The compact permanent-magnet design, the moderate power consumption, and the good performance at low gas pressure make this source attractive for use in high-output neutron generators.

Acknowledgments

The authors would like to thank Amy Sy and Qing Ji for fruitful discussions and advice and Steve Wilde and Mary Stuart for their technical support.

This work was supported by the Office of Proliferation Detection (NA-22) of the US Department of Energy at the Lawrence Berkeley National Laboratory under contract number DE-AC02-05CHI1231.

References

[1] B. A. Ludewigt, R. P. Wells, and J. Reijonen. *Nucl. Instr. and Meth. B*, 261:830–834, 2007.

[2] J. Reijonen, F. Gicquel, S. K. Hahto, M. King, T.-P. Lou, and K.-N. Leung. *Appl. Radiat. Isot.*, 63(5–6):757–763, 2005.

[3] O. Waldmann and B. Ludewigt. 1336:479–482, 2011.

[4] J. Sherman, A. Arvin, L. Hansborough, D. Hodgkins, E. Meyer, J. D. Schneider, H. V. Smith Jr, M. Stettler, R. R. Stevens Jr, M. Thuot, T. Zaugg, and R. Ferdinand. *Rev. Sci. Instrum.*, 69(2):1003–1008, 1998.

[5] J. W. Kwan, R. A. Gough, R. Keller, B. A. Ludewigt, M. Regis, R. P. Wells, and J. Hannes Vainionpaa. *High Energy Physics and Nuclear Physics*, 31(S1):232–235, 2007.

[6] R. Gobin, P.-Y. Beauvais, D. Bogard, G. Charruau, O. Delferrière, D. De Menezes, A. France, R. Ferdinand, Y. Gauthier, F. Harrault, P. Mattéi, K. Benmeziane, P. Leherissier, J.-Y. Paquet, P. Ausset, S. Bousson, D. Gardes, A. Olivier, L. Celona, and J. Sherman. *Rev. Sci. Instrum.*, 75(5):1414–1416, 2004.

[7] J. J. Croat, J. F. Herbst, R. W. Lee, and F. E. Pinkerton. *J. Appl. Phys.*, 55:2078–2082, 1984.

[8] J. Alderman, P. K. Job, R. C. Martin, C. M. Simmons, and G. D. Owen. *Nucl. Instr. and Meth. A*, 481:9–28, 2002.

[9] C. H. Chen, J. Talnagi, J. Liu, P. Vora, A. Higgins, and S. Liu. *IEEE Trans. Magn.*, 41(10):3832–3834, 2005.

[10] G. J. Csikai. *CRC Handbook of fast neutron generators Volume I.* CRC Press, Boca Raton, Fl, USA, 1st edition, 1987.

[11] S. Ishii and H. Amemiya. *Rev. Sci. Instrum.*, 61:270–272, 1990.

[12] T. Taylor and J. S. C. Wills. *Nucl. Instr. and Meth. A*, 309:37–42, 1991.

[13] Z. Q. Xie and C. M. Lyneis. *Rev. Sci. Instrum.*, 65(9):2947–2952, 1994.

[14] D. M. Goebel and I. Katz. *Fundamentals of Electric Propulsion: Ion and Hall Thrusters.* John Wiley and Sons, Inc., New York,NY, 1st edition, 2008.

[15] L. Schächter, S. Dobrescu, Al. I. Badescu-Singureanu, and N. Baltateanu. *Rev. Sci. Instrum.*, 69(2):706–708, 1998.

[16] S. Gammino, G. Ciavola, L. Celona, L. Torrisi, D. Mascali, S. Passarello, and A. Galata. *Rev. Sci. Instrum.*, 77:03B511, 2006.

[17] J. Jolly and J.-P. Booth. *J. Appl. Phys.*, 97:103305, 2005.

[18] R. Gobin, A. France, P.-Y. Beauvais, O. Delferrière, D. De Menezes, and R. Ferdinand. *Rev. Sci. Instrum.*, 69(2):1009–1011, 1998.